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2281004 CORNELL UNIVERSITY
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, N.Y.

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ON A POSSIBLE CLASS OF GALACTIC RADIO SOURCES

by

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Abstract

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In a previous paper it was shown that the steady state theory of the universe can be reconciled with the Cambridge counts of radio sources if a substantial fraction of the sources lie within the galaxy and have a certain set of properties. In this paper we describe an astrophysical mechanism which might give rise to such a distribution of galactic sources. The mechanism consists in the rotational instability of gravitationally contracting low mass stars, and the consequent conversion of rotational energy into magnetic and relativistic particle energy.

If the radio data are correct this scheme will work only if certain extreme conditions are satisfied, namely if:

(a) about 80 percent of the galactic background emission is due to the sources rather than to emission from the interstellar gas,

(b) the amount of matter locked up in the sources is about the maximum permitted by dynamical arguments concerning the "missing matter" in the galaxy,

(c) the distribution of radio sources is highly anisotropic at flux levels below about $0{\cdot}1.10^{-26}$ w(c/s)$^{-1}$ m^{-2}. further.

These and other predictions of our model will probably be tested in the near future.

1. Introduction

Although it seems to be generally accepted that most of the discrete radio sources observed at high galactic latitudes are extragalactic, the evidence in favour of this view is by no means compelling. In fact, it is possible to construct a model consistent with all the radioastronomical data in which most of the sources observed at a given flux level $\lesssim 10$ flux units (1 flux unit = 10^{-26} $w(c/s)^{-1}$ m^{-2}) lie within the galaxy (1). This model was constructed in order to show that the steady state theory of the universe can be reconciled with the Cambridge counts of radio sources. The resulting model is fairly closely specified, in the sense that approximate values can be estimated for the median intrinsic radio luminosity, size, concentration and spatial distribution of the galactic radio sources.

This model has recently been criticised by Scott (2).* Most of his arguments involve statistical considerations which in our present state of knowledge are weighty but not decisive. His main argument, however, is of critical importance. In section 2 we show that according to the present radio data this argument is not necessarily valid. In view of this, and of the general importance of the issues involved, we have thought it worth while to seek a plausible astrophysical mechanism which might account for the existence of a galactic population of sources with the computed characteristics. The main aim of this paper is to describe such a mechanism. Whether it actually operates we cannot be sure, but its links with known or already suggested processes

* I am grateful to Dr. P. F. Scott for showing me his paper before publication.

indicate that our model of a galactic population of radio sources is not astrophysically unreasonable.

In section 2 we recompute the parameters of the galactic sources in the light of developments which have occurred since our previous paper (1) was written. In section 3 we derive the likely astrophysical properties such sources would be expected to possess, and in section 4 we propose a particular mechanism which might lead to the realisation of these properties, namely, the rotational instability of a gravitationally contracting star of low mass and the consequent conversion of rotational energy into magnetic and relativistic particle energy.

2. The Basic Parameters of the Galactic Radio Sources

In (1) we derived the basic parameters of the galactic radio sources from a consideration of various radio and optical data. Since then some new data have been published which permit a more detailed analysis. We begin by recalling the main features of our previous discussion. To allow for a dispersion in the intrinsic radio luminosities of the galactic sources we arbitrarily introduced a luminosity function of the same form as Ryle and Clarke (3) proposed for the extragalactic sources, namely

$$\rho(P) = \left(\frac{P_o}{P}\right)^{3/2} \rho(P_o)\, e^{-l^2/2}$$

where

$$l = \log_{10} \left(\frac{P}{P_o}\right).$$

Here ρ is the space density of galactic sources of luminosity P. The luminosity function for galactic sources whose measured flux-density exceeds some given quantity is then $P_o^{3/2}\ \rho(P_o)\ e^{-l^2/2}$, for which the median luminosity is P_o. A direct analysis of the source counts corrected for the steady state red shift effect, together with data on optical identifications, then leads to a determination of $\rho(P_o)\ P_o^{3/2}$

$= X$, say. To determine $\rho(P_o)$ and P_o separately we follow Ryle and Clarke (3) and impose the requirement that the galactic sources must appear to be distributed isotropically around us, in order to accord with observation. This implies that down to the lowest flux level of the observations the counts are not reaching out to the nearest edge r of the distribution. Hence P_o/r^2 cannot exceed some value S_o, say. But then $\rho(P_o)\ P_o r > X/S_o^{1/2}$. Now $\rho(P_o)\ P_o r$ determines the contribution of the sources to the background radio brightness in the direction of the nearest edge, and this must not exceed the observed brightness in that direction. It turns out in fact that $X/S_o^{1/2}$ is of the same general order as the observed brightness. Hence an appreciable fraction of the galactic radiation in that direction must be due to the sources, and $P_o/r^2 \sim S_o$.

We now attempt a more precise discussion. The most important property of our model is the flux level S at which the anisotropy in the distribution of the galactic sources becomes large enough to detect. If S can be estimated with fair precision a direct observational test of our model will be possible. As we have just seen, S can be determined if we know the fraction f of the galactic background emission which is due to the sources; the larger the value of f the smaller the value of S (in fact $S\sim 1/f^2$). The determination of this fraction is one of the main problems of galactic radioastronomy. Ten years or so ago, it was widely believed that $f\sim 1$ (Ryle (4,5), Westerhout and Oort (6), Hanbury Brown and Hazard (7)), but opinion later shifted in favour of $f\sim 0$, the emission being attributed to synchrotron radiation produced by interstellar relativistic electrons (Kiepenheuer (8), Ginzburg (9)). This interstellar mechanism is the one generally accepted today. Nevertheless, we claim that the value $f\sim 1$ cannot be ruled out by the present radio data.

The two main arguments against $f\sim 1$ are (a) that the radio sources are unlikely to have the halo-like distribution characteristic of the galactic background and (b) that the sources and the background have different spectra. However, according to Baldwin's recent results (10), the galactic background in fact has a mainly disk-like structure, so that argument (a) may no longer apply. In addition, argument (b) is inconclusive. In the first place we note that the spectrum of the galactic background is not yet well established. The Cambridge workers (Turtle et al (11)) find a curved spectrum, with the spectral index dropping from 0.9 at 178 Mc/s to 0.0 at 38 Mc/s. On the other hand more recent measurements at lower frequencies (12,13) suggest that the spectral index has the constant value of ~ 0.5 between 178 Mc/s and 10 Mc/s. At still lower frequencies the flux goes through a maximum and then decreases in a manner suggestive of absorption in regions of ionised gas. It is possible that at higher frequencies, e.g. 400 Mc/s, the Cambridge spectral index of 0.9 is correct.

As regards the spectra of the sources there is now available the extensive survey of Conway, Kellermann and Long (14). For our purposes this survey is misleading in two ways. Firstly, the sources are selected on the basis of their measured flux density and hence of their contribution to $\Sigma\rho P^{3/2}$. On the other hand the sources contribute to the integrated emission in a manner measured by $\Sigma\rho P$. Thus the intrinsically weaker sources make a more important contribution to the integrated emission, and so to its net spectrum, than they do to the spectral sample of CKL. For instance, with our adopted luminosity function, sources with $P < 0.2P_0$ contribute 85% of the integrated emission but constitute only 24% of that part of the spectral sample which consists of galactic sources. There is thus no reason to expect that the median spectrum of the CKL survey should resemble the spectrum of the galaxy, even if $f \sim 1$.

However, if we accept that the spectrum of the galaxy is steeper at high frequencies than at low frequencies, we would expect $f \sim 1$ to imply that, say, $\sim$25% of the galactic sources also have such a spectrum. Now according to CKL only $\sim$10% of the sources with a flux density exceeding 20 flux units (which are nearly all extragalactic) have a curved spectrum. As the limiting flux density is reduced the proportion of galactic sources will increase (see table 1 of (1)), and so the proportion of sources with curved spectra would be expected to increase. However this effect is not present in the CKL survey. This is the second point at which that survey is misleading. For, as CKL point out, their survey is not complete down to some limiting flux density. Their sources were chosen on the basis of the availability of good flux measurements over a wide range of frequencies. This mode of selection tends to discriminate against sources with flat spectra at low frequencies or steep spectra at high frequencies, especially at the lower flux levels. Indeed in the flux range between 10 and 20 flux units only about one-third of the expected number of sources is represented.

Fortunately there exists another spectral survey which _is_ complete down to a limiting flux level (Kellermann and Harris (15)). It is less extensive than the CKL survey in that the spectral data are based on observations at only two frequencies [86 Mc/s (Mills, Slee and Hill (16)) and 960 Mc/s (15)], but its completeness makes it more useful for our purpose. In this survey the median spectral index _does_ increase as the flux level decreases. This is shown in table 1, which is taken from (15).

Table 1

960 Mc/s Flux Density Relative to Hydra A	No. of Sources	Median Spectral Index Relative to Hydra A
>0.06	36	-0.10
0.05 - 0.06	34	-0.01
0.04 - 0.05	26	-0.03
0.03 - 0.04	54	+0.07
0.025 - 0.03	111	+0.09
0.022 - 0.025	120	+0.15

According to CKL the spectral index of Hydra A is 0.87, so the median spectral index increases from 0.77 at high flux levels to 1.02 at low flux levels. Since this spectral index refers to the high frequency range, this is the behaviour we would expect if $f \sim 1$. On the other hand, Kellermann and Harris suggested that the effect might be instrumental, or that it might arise from the red shift if the sources are all extragalactic. Another possibility is that it may be due to evolutionary effects in a non-steady state universe. In our model this latter effect is, of course, absent, and the red shift effect would be too small to be responsible. Further observational work should decide whether the effect is in fact instrumental.

It appears then that according to the present radio data it is permissible to assume tentatively that $f \sim 1$. We can roughly estimate the fractional contribution of the interstellar radiation by noting that in certain directions the galactic background is about one percent polarised at 408 Mc/s (17,18). Unless the magnetic fields in the discrete sources are correlated, this polarised radiation must arise from the interstellar component. A reasonable value for the degree of polarisation of the interstellar component at 408 Mc/s, allowing for Faraday dispersion, is 5% (19). Accordingly the interstellar contribution may be about 20% of the whole.

This suggested reduction in the intensity of the interstellar synchrotron emission has the advantage that it would remove a well-known discrepancy (e.g. 20,27) between the flux of secondary relativistic electrons in the galaxy and the flux required to account for the observed emissivity. Since cosmic ray protons have a path length of ~ 5 gm/cm^2, the expected flux of secondary electrons is about 0.5% of the proton flux, whereas the ratio required to account for the observed emissivity $\sim 5\%$ for a magnetic field strength of $5 \cdot 10^{-6}$ gauss. This discrepancy can be resolved by assuming that the radiating electrons are not secondaries, but are accelerated in the cosmic ray sources along with the protons. On our present model this assumption would no longer be necessary. This point will presumably soon be checked by satellite or rocket experiments.

It is important to note that the ratio f may be quite different from unity in other galaxies, both because the number of discrete sources will vary with the size, age and perhaps type of the galaxy, and because the interstellar contribution may depend very sensitively on the magnetic field strength (21). Presumably galaxies like Andromeda, which possesses an extensive halo (23), do not have $f \sim 1$. On the other hand, it is now known (22) that several bright Sc galaxies are like the Milky Way (10) in having essentially no radio halo. In such cases the magnetic field in the halo region is presumably weak, so that either the field strength increases fairly rapidly as the galaxy is approached or else $f \sim 1$.

These considerations are relevant to two of the criticisms recently brought against our model by Scott (2). He notes that we would expect the fraction of galactic sources to increase as the flux level decreases, and he then claims that there is no sign of this trend in the distributions of intrinsic properties of the sources in different ranges of flux density. However, as we have just seen, there is some evidence of a trend in the distribution of spectral indices, although it is not yet ruled out that the effect is instrumental. Scott's most crucial argument is that the difference in spectra between the galaxy and the sources implies a low value of f ($f<\sim 0.2$ at 178 Mc/s) and so a high value of S ($>\sim 2$ flux units). On the other hand, he argues, we already know that there is no detectable anisotropy at 2 flux units. According to our present discussion, however, there may be no significant difference in the spectra, and it is possible that $f\sim 1$. In this case $S\sim 0.1$ flux units, which lies below the lower limit of the existing surveys.

We now recompute the basic parameters of the galactic radio sources. The minimum sky brightness temperature at 178 Mc/s is 80°K (24). Of this, about 28°K must be attributed to the extragalactic background (11). Taking $f\sim 1$, we find an upper limit for $\rho(P_o)P_o r$ of 10^{11} $w(c/s)^{-1}$ $ster^{-1}$, which is twice the value found in (1) where we made an allowance for the presumed difference of spectra. Since the counts imply (1) that

$$\rho(P_o)P_o{}^{3/2} = 4.10^{13}\ w^{3/2}\ (c/s)^{-3/2}\ pc^{-3}\ ster^{-3/2},$$

we now have

$$\frac{P_o}{r^2} = 0.02 \text{ flux units},$$

and

$$\rho(P_o)r^3 = 5{\cdot}6.10^5.$$

These changes have the effect of lowering the flux density at which the counts drop off significantly because one is observing out towards the edge of the distribution. There will now be a 16% drop in the number of galactic sources in the direction of the nearest edge at 0.2 flux units instead of at 0.8 flux units as in (1). This reduces the correction we made for this effect without, however, upsetting the agreement between our model and the counts of Ryle and Neville (25). It also reduces the flux level at which anisotropy should be detectable. After allowing for the statistical errors of the observations, the diluting effect of the extragalactic sources, and the uncertainties in the parameters of the galactic sources, we conclude that $S \sim 0.1$ flux units, the value we quoted above.

Finally we attempt to estimate the value of r. In (1) we assumed that $r \sim 200$ pc. However Baldwin (10) has discovered that the galactic background has a half-thickness on each side of the galactic plane of ~ 400 pc. Since in our model this background is mainly due to the radio sources, we take this to mean that these sources have a disk-like distribution with a thickenss ~ 400 pc. The degree of flatness of this disk is not well determined from Baldwin's observations, so we shall take $r \sim 400$ pc, although the corresponding direction (that of the minimum background temperature) is actually at a galactic latitude of 50° (24) rather than 90°. With this value for r we have

$$P_o = 3.10^{10}\ w(c/s)^{-1}\ ster^{-1}\ ,$$

and

$$\rho(P_o) = 10^{-2}\ pc^{-3}.$$

These values are the same as in (1), the change in our estimate of r exactly compensating for the change in our estimate of $\rho(P_o)P_o r$. This compensation applies also to the parameters of the small-scale distribution of the sources, e.g. the size of the local hole that has to be introduced. In addition, a typical source still has a diameter of about 10^{15} cm.

We can summarise this discussion by saying that we have to account for a distribution of galactic radio sources of median luminosity $\sim 3.10^{10}$ $w(c/s)^{-1}$ $ster^{-1}$, diameter $\sim 10^{15}$ cm and concentration $\sim 10^{-2}$ pc^{-3}, occupying a disk of half-thickness ~ 400 pc.

3. Astrophysical Properties of the Galactic Sources Inferred from the Radio Data

3.1 The mass and energy content of a source

Since no radio source at high galactic latitude has been optically identified with a galactic object, our hypothetical sources must be optically very faint. Now according to our model many of these sources lie within 20 parsecs of the sun. It follows that they must have a large absolute photographic magnitude. If there is a star at the centre of the source this star must have a mass $<\sim 0.1 M_\odot$. Such a star has a radius $\sim 0.1 R_\odot$; accordingly, its gravitational energy $\sim 10^{48}$ ergs. An explosion (whose cause we consider later) might reasonably release a fraction 10^{-3}-10^{-2} of this gravitational energy, that is,

10^{45}-10^{46} ergs. We shall suppose that most of this energy is transformed into magnetic energy during the explosion and that a substantial fraction of this magnetic energy is then dissipated into radiation and fast protons, as probably happens in a solar flare. This solar flare analogy suggests that as much as $\sim$10% of the energy may be transformed into $\sim$0.1-1 BEV protons (26). These protons then collide with the ambient gas and transfer $\sim$10% of their energy to decay electrons whose individual energy $\sim$1-100 Mev (27). There results $\sim 10^{43}$-10^{44} ergs of relativistic electrons, whose synchrotron radiation in the magnetic field will be in the radio region for fields in the range 10^{-1}-10^{-4} gauss.

To see whether this range of values for the magnetic field is reasonable we will use our result that the sources have a diameter $\sim 10^{15}$ cm. This means that the region containing the bulk of the magnetic energy has expanded in linear dimensions by a factor $\sim 10^{5}$, so that the magnetic energy is reduced by this factor to 10^{40}-10^{41} ergs (if magnetic flux is conserved during the expansion). The corresponding value of the magnetic field ~ 2-6.10^{-2} gauss, which lies within the required range. It is important to realise that the magnetic field will build up to this value only if its dissipation time scale t_d is not less than the time-scale t_t for transferring the explosive energy to the magnetic field. Otherwise the field will be reduced by the factor $(t_d/t_t)^{1/2}$. The mechanism will thus produce a radio source even if $t_d \sim 2\cdot 5.10^{-5}$ t_t.

These time scales cannot be calculated directly, but we can impose the requirement that the source must have a radio luminosity $\sim 3.10^{10}$ w(c/s)$^{-1}$ ster^{-1} at 178 Mc/s. With an effective bandwidth $\sim 3.10^{8}$ c/s, the corresponding rate of emission of energy in the radio region $\sim 10^{27}$ ergs/sec. If we neglect all sources of energy loss for the electrons other than the synchrotron process itself, then the 10^{43}-10^{44} ergs of electron energy will have to be consumed in 10^{16}-10^{17} secs. This time represents t_t, t_d, the time-scale t_e for the production of the electrons from the protons, or the time-scale t_s for synchrotron loss, whichever is the longest. For $H \sim 10^{-2}$ gauss and an electron energy of 100 Mev, t_s is only about 10^{10} secs, so t_t, t_d or t_e must be 10^{16}-10^{17} secs. Since the electrons lose energy at a rate 10^{6}-10^{7} times faster than they receive it, the total electron energy at any one time $\sim 10^{37}$ ergs, which is comfortably less than the magnetic energy of $\sim 10^{40}$-10^{41} ergs. These energies are not far from the minimum total energy of $\sim 10^{39}$ ergs estimated in (1). A final point worth noting at this stage is that the emission rate in the visible is likely to be about a hundred times greater than in the radio region, that is, about 10^{29} ergs/sec. This represents about 3.10^{-5} of the sun's luminosity, and is consistent with the requirement that the galactic radio sources be optically faint.

3.2 The spatial distribution of the sources

Not much is known about the galactic distribution of faint stars. Following Oort (28) we will place limits on this distribution from dynamical considerations. Various attempts have been made to determine the total density of matter near the sun (28,29,30,31,32) with results ranging up to $\sim 0.2 M_\odot$ pc^{-3} (30,32). Of this density about half can be attributed to known material (stars and gas) leaving half unaccounted for. This unknown material probably consists of molecular hydrogen gas and faint stars. We can attempt to distinguish between these two possibilities by using the fact that the molecular hydrogen is probably mainly confined to a thin disk lying in the plane of the galaxy (33). Now, the rotation curve of the galaxy indicates that the total mass in a column of unit cross-section perpendicular to the plane of the galaxy and passing through the sun may be as large as 200 $M_\odot\ pc^{-2}$ (34) (using the recent value of 10 kpc for the distance from the sun to the centre of the galaxy). A similar value is obtained if we suppose that the mass luminosity ratio in a cylinder perpendicular to the galactic plane is the same as for M31 at a corresponding distance from the centre (34). Now the contribution of the known material and also of the possible molecular hydrogen is less than 50 $M_\odot\ pc^{-2}$ (33). Accordingly the surface density of the faint stars may exceed $\sim$150 $M_\odot\ pc^{-2}$. This result is consistent with the known kinemetical properties of stars (especially K giants) if the faint stars are distributed like halo population II (Oort quoted in (34)). If we take $\sim$2 kpc as the thickness of this distribution, we obtain for the density of faint stars a possible lower limit of 0.075 $M_\odot\ pc^{-3}$.

If these stars have an average mass $\sim$0.1 $M_\odot$, their concentration may be at least 0.75 pc^{-3}. We must now estimate what fraction of these stars are at present in an active phase as radio sources. These stars have presumably been forming for about 10^{18} secs. Since the active phase was estimated to last 10^{16}-10^{17} secs, only 1-10% of the faint stars would be expected to be radio sources. Their concentration may thus be $\sim(0.75-7.5).10^{-2}$ pc^{-3}, which is consistent with our estimate from the radio data of 10^{-2} pc^{-3}.

We require that this active fraction of the sources have a distribution which is only 400 pc thick, rather than the 2 kpc of the parent distribution. Now there is a correlation between the age of a set of stars and the thickness of their distribution, the younger stars having the thinner distribution. Hence the active phase is presumably a feature of recently formed stars. This would fit in with the fact that pure population II objects (globular clusters and (normal) E galaxies) have not been detected as radio sources. According to the estimate of Eggen, Lynden-Bell and Sandage (35), the thickness of 400 pc implies that the active stars started to form $\sim 10^9$ years ago. But this time is of the same order as the Kelvin-Helmholtz-Hayashi contraction time for stars of mass $\sim 0.1\ M_\odot$ (36). We thus see that it is possible that the active stars are still in the stage of gravitational contraction. Now it has often been suggested that during its contraction a star passes through a phase of violent activity, usually associated with the onset of rotational instability. The most detailed recent discussion of this possibility has been given by Hoyle (37) and Fowler, Greenstein and Hoyle (38) in connection with their studies of the origin of the solar system and of the behaviour of T Tauri stars. In the next section we examine the possibility that our galactic radio sources are young low mass stars passing through a phase of rotational instability. We shall see that this hypothesis is not unreasonable.

4. Rotationally Unstable Stars as Radio Sources

4.1 The hydromagnetic transfer of angular momentum

It is well known that if angular momentum is conserved during the gravitational contraction of a protostar the angular velocity rises sufficiently for the condensation to become rotationally unstable. According to the analysis of Jeans (39) it then throws out a disk of material in the equatorial regions. This disk will presumably be magnetically connected with the main body of the protostar since the magnetic field present in the original interstellar material is unlikely to be completely squeezed out during the contraction. As the protostar continues to collapse its magnetic coupling to the disk will, if strong enough, tend to keep its angular velocity the same as that of the disk. Most of its angular momentum will then be transferred to the disk, which will spiral outwards. The contracting condensation rapidly becomes rotationally stable, so little further material is added to the disk.

The quantitative discussion of this process is not quite straightforward because under the natural assumption that magnetic flux is conserved during the contraction process the final value of the stellar magnetic field would be unrealistically large. There is thus a magnetic field problem as well as an angular momentum problem associated with the process of star formation. Mestel and Spitzer (40) have suggested that when the density of the protostar rises to a certain value the ionisation level of the gas and so its conductivity decrease to the point at which the magnetic lines of force are no longer frozen into the material. The neutral component then collapses across the field lines and there is no further amplification of the magnetic field strength.

Hoyle (37) has attempted to resolve the combined angular momentum and magnetic field problems by dividing the process of star formation into three parts:

(a) the initial phase in which the lines of force are frozen into the material and angular momentum is transferred to the surrounding interstellar medium,

(b) the Mestel-Spitzer phase in which angular momentum is conserved,

(c) the Kelvin-Helmholtz phase in which there is again freezing-in of the lines of force.

The angular momentum transfer in (a) is regarded as destroying only the peculiar rotation of the condensation relative to its surroundings -- the general rotation of the galaxy of order 10^{-15} sec^{-1} survives this stage. In phase (c) the increase of temperature associated with the increasing opacity produces sufficient ionisation to restore the freezing-in of the magnetic lines of force. It is in this phase that the protostar becomes rotationally unstable and loses most of its angular momentum to the resulting disk.

This picture of a contracting star is attractive because in addition to resolving the angular momentum and magnetic field problems it leads to a natural theory for the origin of the solar system. Hoyle (37) has shown that if the planets are regarded as condensations in the disk surrounding the rotationally unstable protosun many of the quantitative properties of the solar system can be accounted for, such as its distribution of angular momentum, and the masses, distances and chemical compositions of the planets. A further point of particular relevance for our problem concerns the fate of the rotational energy lost by the protostar during the transference of angular momentum. This energy must be transformed into magnetic energy through the differential rotation of protostar and disk. This magnetic energy can then be dissipated into fast protons and electrons, as discussed in the last section. Evidence for the occurrence of this dissipation process is provided by the overabundance of Li in T Tauri stars relative to the solar abundance (41, 42). These stars are highly active and are believed to be still undergoing gravitational contraction (43). Hoyle and others have suggested that they are passing through the phase of rotational instability. The overabundance of Li can then be attributed to spallation reactions induced by the high energy protons (41); this turns out to require a net proton energy of the order estimated here, that is, about 10% of the rotational kinetic energy. Similar considerations apply to the overabundance of Li on the earth (44,38).

4.2 T Tauri stars as radio sources

T Tauri stars are believed to have a mass $\sim 1\ M_{\odot}$, but we shall discuss them as radio sources before considering the low-mass stars since there is observational data available for them which will serve as a check on our order of magnitude estimates. According to Hoyle's

(37) dynamical arguments the rotational kinetic energy which must be dissipated $\sim 10^{46}$ ergs, so that the total cosmic ray proton energy $\sim 10^{45}$ ergs, the mean proton energy being about 1 Bev. As we have just mentioned these values are of the right order of magnitude to account for the abundance of Li in T Tauri stars and in the solar system. The resulting total relativistic electron energy should be about 10^{44} ergs, the mean electron energy being about 50 Mev.

To estimate the magnetic field strength we proceed as follows. The radius of the protostar when it becomes rotationally unstable is about 3.10^{12} cm (37). The magnetic energy of 10^{46} ergs cannot be confined by the relatively light disk which will presumably be forced to expand, even if some of the magnetic energy is stored in the protostar as Hoyle suggests. The observed size of the nebula surrounding T Tauri is about 10^{16} cm (45), so we shall assume that the disk expands to this extent. If we also assume that magnetic flux is conserved during the expansion, and that the initial thickness of the disk is about one-tenth of its initial radius, then the final value of the magnetic energy $\sim 3.10^{41}$ ergs, corresponding to a magnetic field $\sim 10^{-3}$ gauss. In a magnetic field of this strength 50 Mev electrons radiate in the vicinity of 15 Mc/s.

We next consider what fraction of the electron energy goes into synchrotron radiation. The particle density in the T Tauri nebula $\sim 10^{4}$ cm^{-3} (45), which implies that 50 Mev electrons moving in a magnetic field of 10^{-3} gauss will lose energy about one hundred times faster through ionising collisions and the production of bremmstrahlung than through synchrotron radiation. Accordingly, the energy available for synchrotron radiation $\sim 10^{42}$ ergs.

To estimate the radio luminosity of the T Tauri stars we need to know the time-scale for the release of the rotational kinetic energy. Hoyle took this time-scale to be 10^{14} secs, which is comparable with the gravitational contraction time. This choice leads to a reasonable value for the expected concentration of T Tauri stars. For our rough purposes we may assume that the star formation rate has been constant for the last 10^{18} secs. Since the concentration of stars of solar mass is about 0.1 pc^{-3}, the expected concentration of T Tauri stars will be $\sim 10^{-5}$ pc^{-3}, in agreement with the (equally crude) observational estimate (43).

Since the 10^{42} ergs of energy available for synchrotron radiation is released in 10^{14} secs, the radio luminosity of a typical T Tauri star should be 10^{28} ergs/sec. With an assumed bandwidth $\sim 3.10^{8}$ c/s, the luminosity in the vicinity of 15 Mc/s should be about 3.10^{11} $w(c/s)^{-1}$ $ster^{-1}$. We shall adopt this same luminosity at 178 Mc/s, the frequency of the Cambridge source count surveys, since our estimates are too rough to justify allowing for the spectrum of the sources. However it is important to consider possible absorption effects in the nebulae surrounding the T Tauri type stars. For T Tauri itself Osterbrock (45) has found a free electron density $\sim 4.10^{3}$ cm^{-3} and an electron temperature $\sim 7,500°K$. Since the radius of the nebula $\sim 10^{16}$ cm, its optical depth will be unity at a frequency close to 178 Mc/s. The maximum intensity of T Tauri should thus occur close to this frequency, the actual frequency depending on the spectral index of the source.

This possible occurrence of absorption at intermediate frequencies provides a tentative explanation for the peculiar spectra of the sources CTA 21 and CTA 102 (14) which have maxima in the region of 900 Mc/s. If these sources have a free electron density five times as great as in the T Tauri nebula the effect would be explained. The fact that no optical object has been identified with the sources can also be explained on the assumption that the protostars involved are at an earlier stage of their development than T Tauri. Then they would be more like the Herbig-Haro objects, one at least of which has properties very similar to the T Tauri nebula, but with a very faint central star (46,45). Such an object placed at, say, 200 pc would have an apparent magnitude of only about 15.

Our rough estimate of 3.10^{11} $w(c/s)^{-1}$ $ster^{-1}$ for the radio luminosity of a typical T Tauri star has two interesting implications. The first is that the quantity $\rho P^{3/2}$ for these stars is 2.10^{12}, whereas $\Sigma\rho P^{3/2}$ for all the galactic sources is 10^{14} (1). Hence $\sim$2% of the galactic sources should be stars which are optically fairly bright. The question then arises whether these sources can be optically identified. For $S>10$ flux units one-half of all the observed sources are galactic on our model (1), so we should expect $\sim$1% of all the sources in this flux range to be fairly bright stars, that is, about 50 sources in all. Now the 50 brightest T Tauri stars have photographic magnitudes <13 (43). Most of these stars lie at low galactic latitudes where there are more than 100 stars per square degree in this magnitude range. Optical identification will thus be possible only if the radio positions are sufficiently accurate that the probability of a star lying within the error rectangle by chance is substantially less than one percent. Such accuracy appears to have been recently achieved (48).

The second implication involves the reverse problem, that is, attempting to identify T Tauri stars as radio sources. T Tauri itself, at a distance of about 170 pc, should have a flux density of about 1 flux unit at frequencies high enough for absorption to be unimportant. This, of course, is a rough estimate since in particular no allowance has been made for the spectrum of the source, but it does suggest that its flux may be measurable. At the moment the only stars other than the sun which have been detected as radio sources are some very close flare stars (47). Their radio emission is highly variable and is correlated with the flare activity, as in the case of the sun. This implies that energy cannot be stored in either the relativistic protons or the electrons for a time long compared with the time-scale for the occurrence of the flares. Since the radio sources we are concerned with are presumably fairly steady we require this to be no longer true when there is a vast envelope surrounding the star.

4.3 Low mass stars as radio sources

We cannot expect to perform an accurate calculation of the radio luminosity of a rotationally unstable star of mass $\sim 0.1\ M_{\odot}$. Instead we shall attempt to make it plausible that in scaling down the estimates of section 4.2 we might arrive at the required median luminosity of 3.10^{10} w(c/s)$^{-1}$ ster^{-1}. The rotational kinetic energy scales as $\alpha^3 m^{5/3}$, where m is the mass of the star and α is a measure of its degree of central condensation when rotational instability sets in -- the square of the radius of gyration being then $2/5\ \alpha r^2$. The radius r itself scales as $\alpha^{-2}\ m^{1/3}$. For stars of solar mass Hoyle took $\alpha \sim 0{\cdot}25$; we shall take $\alpha \sim 0{\cdot}5$ for stars of mass $0.1\ M_\odot$. With this assumption the available energy decreases by a factor ~ 5, and the initial radius of the disk decreases by a factor ~ 10. Since the final radius is required to be $\sim 10^{15}$ cm, this radius also decreases by a factor ~ 10. Accordingly the final magnetic field increases by a factor ~ 10. For a fixed mean electron energy and ambient particle density the ratio of the time-scales for synchrotron loss to both ionisation and bremmstrahlung losses varies as H^{-2}, so we shall now neglect both the latter loss processes. In addition, if the free electron density $< \sim 10^2\ cm^{-3}$ and the electron temperature $\sim 10^{4\circ}K$, absorption effects will be unimportant for frequencies exceeding ~ 10 Mc/s. The intensity of the galactic background actually appears to have a maximum in the neighbourhood of 5 Mc/s (12,13). This may be due to absorption in the sources, which on our model are mainly responsible for the galactic background, but is more probably due to interstellar absorption, since the frequency at which the maximum occurs appears to depend on galactic latitude.

Finally we consider the time-scale for the release of the rotational kinetic energy. Since the electron energy in the present case $\sim 2.10^{43}$ ergs, we are in the energy range discussed in section 3.1. It was there shown that with this electron energy the sources will have the required luminosity if the time-scale for releasing the energy $\sim 10^{16}$ secs. This time-scale was also shown to be consistent with the required concentration ρ of these sources. We can now see that it is a reasonable one in terms of the present mechanism, since the total contraction time for a (non-rotating) star of mass $\sim 0.1\ M_{\odot}$ has been estimated as 3.10^{16} secs (36). Moreover this time-scale is consistent with our requirement that the star be optically faint. For in contracting at constant angular velocity the protostar loses most of its angular momentum by the time its radius is halved. In this time the amount of gravitational energy released by the contraction $\sim 10^{46}$ ergs, and the corresponding rate of energy release $\sim 10^{30}$ ergs/sec. This represents a luminosity $\sim 2{\cdot}5.10^{-4}\ L_{\odot}$ and a surface temperature $\sim 10^{3}$°K, corresponding to an optically faint object. It is thus plausible that the radioactive low mass stars have the required concentration of 10^{-2} pc^{-3} and radio luminosity of 3.10^{10} w(c/s)$^{-1}$ ster^{-1}.

5. Conclusions

The theory proposed in this paper is extremely tentative. Our main aim has been to suggest that our model of galactic radio sources is not astrophysically untenable. Should direct observational evidence for this model be discovered, e.g. from anisotropy in the distribution of sources of low flux density, then the various processes involved in the present theory should be more carefully discussed.

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